

# Remotely Sensed Tropical Cyclone Structure/Intensity Changes

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## LONG-TERM GOALS

Accurately map the three dimensional structure and intensity changes of tropical cyclones via satellite remote sensing data for both real-time analyses and as input to numerical weather prediction models.

## OBJECTIVES

Develop techniques to map the three-dimensional (3-D) structure of tropical cyclones (TCs) in all-weather conditions. Enable the analyst to determine whether a TC has changed intensity via organization of cloud/rain bands and the formation of an eyewall or eye. Derive a methodology that will work well under all conditions, including at night when poor resolution Infrared (IR) data causes multiple problems.

## APPROACH

Passive and active microwave satellite data will be used to mitigate the inherent limitations of visible and infrared (vis/IR) data used to monitor TC structure and intensity worldwide. Geostationary vis/IR data often enable users to determine storm motion and intensity estimates, but are unable to see through upper-level clouds created within the central dense overcast (CDO). The inability to see through upper clouds degrades real-time warnings and inaccurate nowcasts create poor initial conditions and impair subsequent numerical model forecasts.

Use passive microwave imager data from the current suite of operational and R&D sensors to mitigate vis/IR sensing problems. This constellation includes three Special Sensor Microwave/Imagers (SSM/I) onboard the Defense Meteorological Satellite Program (DMSP) polar orbiter satellites (F-13, 14, 15), the NASA Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI), the Advanced Microwave Scanning Radiometer (AMSR-E) on NASA Aqua, the Coriolis Windsat polarimetric radiometer, three Advanced Microwave Sounding Units (AMSU) on NOAA polar orbiters (N15/16/17), and the Special Sensor Microwave Imager Sounder (SSMIS). Acquire and process all sensors when overflying TCs globally to collect and study applications on TC monitoring (track and intensity).

Utilize 85-89 GHz and 37 GHz passive microwave imager data to map TC structure, with particular focus on inner-core dynamics and eyewall formation processes. Incorporate multiple sensors in order to view eyewall cycle time evolution. Present and publish eyewall replacement cycle observations and

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enable modeling and dynamical TC researcher's opportunity to determine physical mechanism responsible for these short-term intensity variations. Use the microwave imager's ability to map atmospheric moisture very accurately to investigate the relationship between the Saharan Air Layer (SAL) and TC intensity. Utilize the unique TC structural information observed with microwave data (imager and sounder) to extract storm location and intensity values. Take advantage of the "all weather" microwave data sets to extract accurate TC information when vis/IR data are cloud-limited. Investigate methods to extract storm intensity from both imagers and sounders separately and combined into merged algorithm as validation data sets permit more mature methods which highlight the various pluses and minuses attached with each effort.

## WORK COMPLETED

SSM/I passive microwave digital imagery from over 9,000 tropical cyclone overflights has been processed at NRL-MRY. The data processing techniques utilize specific image enhancement methods to produce high quality outputs. TC eyewall cycles have been documented using 1997-2004 data set not possible with earlier studies. The brightness temperature and rainrate products are analyzed by an automated computer vision technique using specific feature screening criteria. The method has been trained using the highest quality aircraft reconnaissance data set available, with most data in the Atlantic basin and results indicate RMSE near 13kts.

Three seasons of total precipitable water (TPW) products have been produced for the Atlantic basin. The near real-time data sets were produced 4/day and routinely used by NOAA G-IV planners to locate very stable and dry Saharan Air Layer (SAL) air masses near TCs. Favorable comparisons with G-IV dropsondes led to submission of NOAA Joint Hurricane Testbed proposal.

Refined microwave imager "morphing" technique which enables enhanced information retrieval from unevenly distributed images over TCs. Key inner-core structural information can be more readily viewed in the morphed animation output.

AMSU passive microwave sounding data from the NOAA-15/16/17 polar orbiters have been processed for the past four (4) years over TCs in both the Atlantic and Pacific basins. Significant effort has been focused on the Atlantic basin due to the availability of high quality aircraft reconnaissance validation measurements. Efforts are focused on correcting for rain contamination in AMSU channels and enhancing overall TC intensity estimates.

## TECHNICAL RESULTS

### **Eyewall replacement cycles:**

This 6.2 effort has pioneered a revised view of TC structural evolution. The inability to routinely "see through" upper-level clouds obscuring eyewall and rainband formation greatly hindered our knowledge of internal storm organization and thus intensity. Partial glimpses of rainbands and eyewalls were possible with vis/IR throughout many storms' lifecycles (especially when well exposed clear eyes permitted accurate inner eye views), but the whole concept of concentric eyewall cycles was thought to be quite rare. Infrequent examples seen via aircraft and land-based radar left us with little understanding about their true frequency and role in storm intensity trends. Passive microwave data from SSM/I, TMI, AMSR-E and AMSU on the NRL-MRY tropical cyclone web page were used to

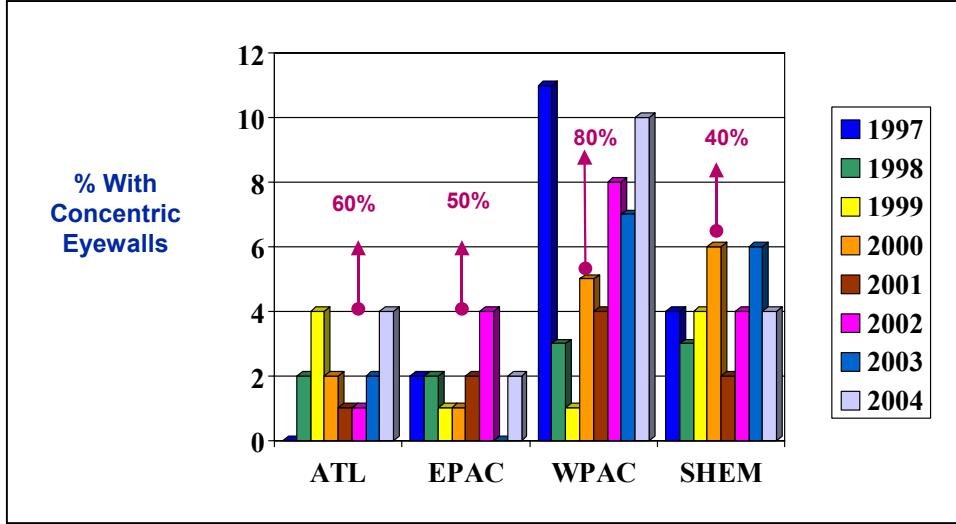
create the database (Hawkins, et al., 2004a, b, and Hawkins, et al., 2001) in addition to a specially processed SSM/I database. The NRL TC web page can be located at  
[http://www.nrlmry.navy.mil/tc-pages/tc\\_home.html](http://www.nrlmry.navy.mil/tc-pages/tc_home.html)

Passive microwave (PMW) data permits TC structure and organization to be “viewed” whenever the constellation of operational and R&D sensors overfly. This has been the basis of the unique perspective provided by the NRL TC web page. Internal eyewall cycles occur more frequently than earlier realized due to inadequate vis/IR sampling. The PMW database reveals a process whereby; 1) a single eye shrinks with time to a small diameter (8-12 nm), 2) a secondary eyewall forms at a larger radii and proceeds to gain strength while limiting inflow of moisture and momentum to the inner-eye, and 3) eventually the inner eye collapses. The outer eyewall then contracts as the storm reintensifies (4) and the eyewall replacement cycle process can continue several times if conditions permit. This cycle occurs over 12-36 hours, with actual time varying due to several unknown factors. The cycle is shorter when “environmental factors” are very favorable for rapid intensification. The replacement cycle lengthens as environmental conditions become hostile or less conducive (shear, dry air entrainment, lower SSTs) and sometimes can stop abruptly.

This structural evolution was highlighted in Cat 5 Hurricane Katrina during August 2005 in the Gulf of Mexico as the storm went from one solid eyewall to double eyewalls prior to landfall. Fortunately, landfall occurred prior to cycle completion or a higher intensity and more damage might have resulted.

A systematic review of passive microwave data during 1997-2004 (Figure 1) reveals that concentric eyewalls are highly correlated with storms reaching 120 kts or higher (Hawkins and Helveston, 2004). Approximately two-thirds (60%) of Atlantic basin storms and three-quarters (80%) of western Pacific typhoons reaching best track intensities of 120 kts or more exhibited concentric eyewalls. WPAC storms reaching Super Typhoon intensity typical form further east than normal and have favorable environmental conditions for many days that permit them to more closely attain the maximum potential intensity (MPI). In contrast, Atlantic-basin storms are typically further west when reaching CAT 3-4-5 status and literally run into unfavorable wind shear, landfall, dry air entrainment or some combination of these factors that weaken the storm and do not permit double eyewall formation.

This correlation is important to: a) TC satellite analysts interpreting passive microwave imagery, b) understanding TC short-term intensity trends, and c) theoretical studies focused on inner-core storm dynamics associated with eyewall evolution (eyewall replacement cycles have become the subject of intense debate on why they form dynamically and how can we modify forecast models to predict their behavior). NRL efforts to publicize eyewall cycles have now led to specific references about these phenomena in official NHC/JTWC TC discussions anytime PMW data reveals these features.



**Figure 1: Number of tropical cyclones reaching a maximum sustained wind speed equal or greater than 120 kts for the Atlantic, Eastern Pacific, Western Pacific and southern hemisphere. The study time frame covers the years 1997-2004. Approximately 60% (two thirds) of storms reaching 120 kts developed concentric eyewalls in the Atlantic, 50% in the eastern Pacific, while the western Pacific statistics reveal ~ 80%. Note the SHEM has a smaller percentage with double eyewalls since few reach in excess of 120 kts.**

## Morphing Passive Microwave Imagery

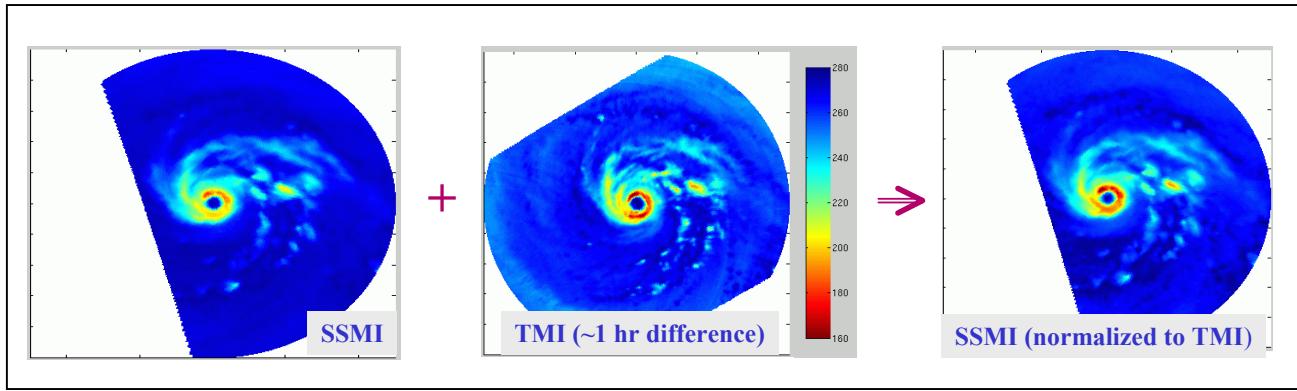
Temporal sampling issues are common with polar orbiter sensors due to their limited refresh times. The typical 1400-1600 km swath is  $\sim$  one half that needed to provide contiguous coverage at the equator from one pass to another. Thus, infrequent inner-core views can make it difficult to interpret the eyewall replacement cycle phase a storm is in at any given time (e.g., inner eye fading or totally collapsed, secondary eyewall beginning). Experienced satellite analysts can typically overcome this hurdle, but it is obvious that assistance would be welcome in easing TC structure understanding.

Tony Wimmers and Chris Velden from CIMSS have implemented a morphing method applied to PMW TC images (Wimmers and Velden, 2004). All SSM/I, TMI, and AMSR-E imagery for a tropical cyclone are assembled and then consecutive images are used to “bridge the time gap”. The morphing applied for this application involves more than just a time-weighted pointwise interpolation of initial and final images (which is sometimes called a “fade” or a “cross-dissolve”). Rather, the initial and final images are warped with time such that their corresponding features advect, stretch, or rotate into one another. This technique has been refined over the past year to include data that is “benchmarked” with the TMI data set. This helps remove potential inconsistencies using slightly different channels such as 85 GHz on SSM/I and 89 GHz on AMSR-E.

Even with five (5) separate passive microwave imagers, a tropical cyclone is overflowed every 4-5 hours on average, although time gaps are irregular, ranging from 30 minutes to 25 hours. An additional complication is that activity in the imagery ranges can include both rapid advection and large-scale, stationary convective development, often overlapping. On the other hand, we can

reasonably assume certain properties in the structure of a TC such as nearly axial symmetry of the wind speed and a “Holland profile” of wind speed as a function of radius (Holland, 1980).

The current TC morphing algorithm strikes a balance between these different kinds of motion and imposes an advection on the microwave signal that is a function of radius and reported maximum wind. The algorithm works by not just blending purely interpolated images into one another, but by rotating the interpolated images throughout the blending process. This creates an effect of rapidly-emerging cells inside large, slower moving areas of convection, which is observed in surface radar imagery, but is not apparent at the original temporal resolution of the microwave imagery. The final result is an enhanced animation permitting improved interpretation of TC inner-core dynamics by near real-time users such as hurricane satellite analysts. This is important when extracting accurate TC intensity estimates that rely heavily on eyewall replacement cycle phases. The method has been transitioned to 6.4 and is now routinely accomplished in near real-time for all storms globally.



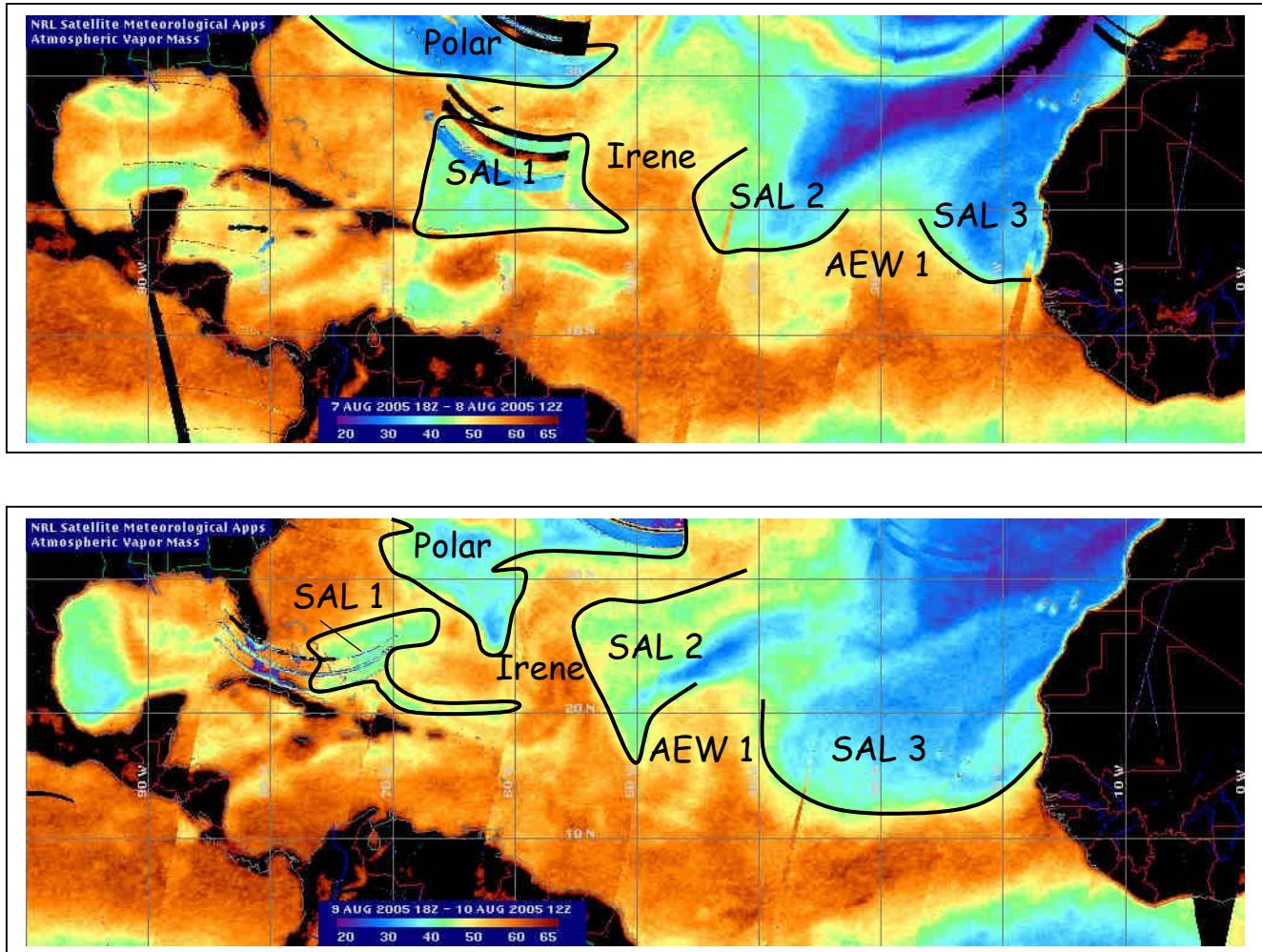
**Figure 2: Process outlining how multiple passive microwave sensors are “base-lined” using TMI data to create a consistent PMW data base for morphing and subsequent animation. Process enables viewer to visualize eyewall cycle evolution easier than with single snapshots. (Wimmers and Velden, 2004).**

### Saharan Air Layer:

The Atlantic basin is viewed by many as a “moist tropical belt” that is highly conducive to tropical cyclone development. Environmental factors such as wind shear, ocean heat content, and surrounding surface pressures are closely monitored when attempting to gauge which incipient tropical waves will develop from the frequent African waves. Evidence now reveals we must track and quantify the very dry stable air associated with the Saharan Air Layer (SAL) as noted by Dunion and Velden (2004). SAL air is incredibly stable and maintains a rigid lid on convection due to a strong inversion at 850-900 mb. SAL air can arrest a system’s development or delay it, depending on the extent of interaction. If SAL air is entrained, then rapid weakening can occur.

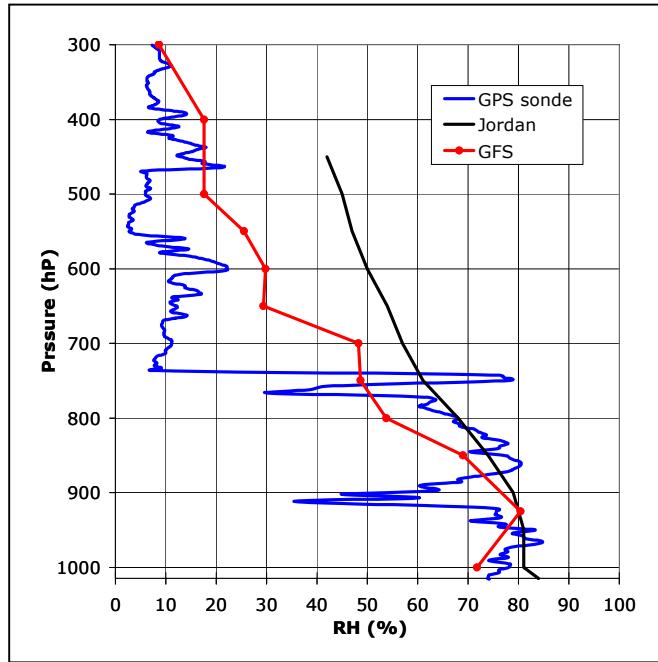
NRL has teamed up with Jason Dunion from NOAA’s Hurricane Research Division (HRD) during the summers of 2003-2005 to create a near real-time monitoring product (Dunion, et al, 2004). Three operational Special Sensor Microwave/Imagers (SSM/I) are used to map the total precipitable water (TPW) across the Atlantic basin every six hours. Very low values of TPW are used as a proxy for SAL air, since non-SAL air has a very moist profile extending well above the typical SAL inversion.

Figure 3 are sample SSM/I TPW products for Hurricane Irene during two snapshots of its lifespan. Dry SAL air is noted in front and behind Irene on 7-9 August, with moist sources to the SE and SW as one might expect. Figure 3 illustrates how a combination of SAL and mid-latitude air from the north pinned Irene in on 9 Sept, limiting its ability to tap moist neighboring regions.



**Figure 3.** Total columnar water or total precipitable water (TPW) created using mosaiced F-13, 14 and 15 SSM/I digital data on 7-9 August 2005 respectively, in near real-time at the Naval Research Laboratory. High values are yellow and brown and are related to hurricane Irene NE of Puerto Rico (retrievals in rain and very humid pixels are permitted to enhance user interpretation). Dry air is blue and highlights Saharan Air Layer (SAL) extending across the northern semicircle of Hurricane Irene with the storm hemmed in by dry SAL air on both sides and mid-latitude polar air to the NW.

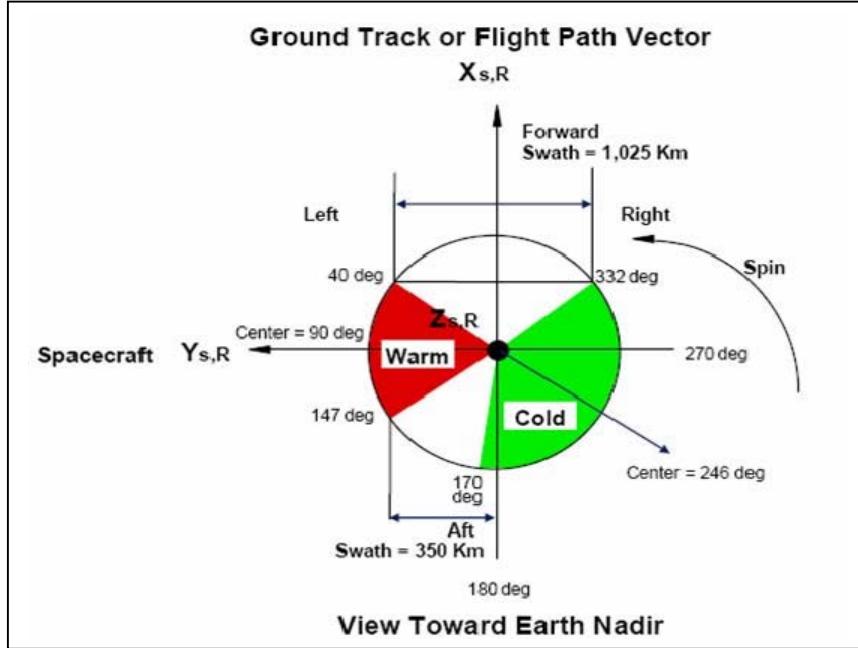
The SAL monitoring product is available via ftp and Internet web page to HRD field personnel and was used daily. Gulfstream G-IV dropsonde locations were coordinated using the NRL TPW products and the global model sensitivity diagnostics. The NRL information permitted drops within specific spots suspected of containing SAL air for verification. Extensive dropsonde and SSM/I TPW data sets are being studied to identify when SAL negatively impacts TC intensity.



**Figure 4: Sample Saharan Air Layer (SAL) sounding acquired from NOAA G-IV jet dropsonde measurements. Strong inversion clearly demonstrated near 750 mb with relative humidities dropping to the 10% range in stark contrast to the mean Jordan sounding shown in black (60% RH near 750 Mb). The NOAA NCEP Global Forecasting System (GFS) model analysis valid at dropsonde time indicates an inability to monitor the intensity and scale of SAL air near the storm. Courtesy of Jason Dunion (NOAA HRD).**

#### Multiple Passive Microwave Views (angles) of Tropical Cyclones:

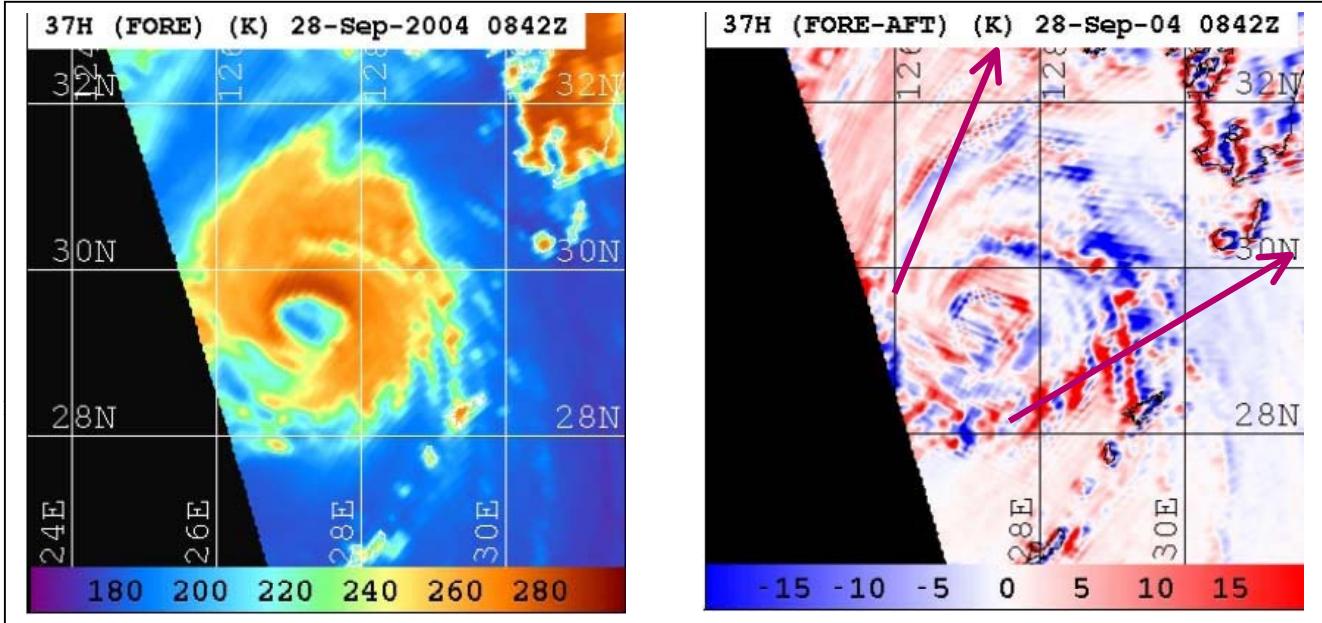
The WindSat polarimetric radiometer provides two viewing angles via both a fore and aft scan as diagramed in Figure 5. This unique sensor attribute enables nearly simultaneous looks at multiple frequencies and provides several opportunities not previously feasible. During 2005, Joe Turk studied WindSat data to determine if storm tilt or shearing could be extracted from the fore/aft scans.



**Figure 5. Schematic diagram illustrating WindSat sensor view angles both ahead and behind the spacecraft during operations. The small 350-km aft swath provides a unique angle that potentially can make several measurements not feasible with any other passive microwave imager.**

Radiative transfer calculations were first completed to model the general behavior of WindSat's channels when exposed to tropical cyclone type conditions. These simulations included approximations to include generic storm tilt. Real life examples highlighting WindSat overflights of TCs with wide ranging shear conditions (no shear to strong shear) were then examined using brightness temperatures at 37 GHz and corresponding shear values derived from combined geostationary cloud and water vapor tracked winds and numerical model analyses throughout the atmospheric layer.

Figure 6 shows how difference images between the fore/aft brightness temperature products can expose TC tilt. Note there is only a small time difference (minutes) between the multiple views due to the 7km/sec spacecraft speed. Multiple storms were tested while also correlating each example with low-upper level shear via the U. of Wisconsin CIMSS shear products using a combined NWP and geostationary cloud/water vapor-tracked wind data set. Apparent storm tilt in WindSat fore-aft products agrees well with shear values.



**Figure 6:** WindSat 37 GHz H pol brightness temperature imagery on the left for Maeri in the western Pacific on 28 September 2004. Note the asymmetric rain and heavy liquid water field (orange/brown) with the storm structure highly skewed in the NW-SE direction. The difference product on the right reveals how the fore-aft views detect the storm tile from the SW to the NE. This agrees with the shear of 16 m/s from 226 degrees determined independently from atmospheric wind data sets. These results are in press in an upcoming WindSat IEEE special issue.

## IMPACT/APPLICATIONS

The concentric eyewall findings revealed in this 6.2 study have permeated a large segment of the tropical cyclone community. Eyewall cycles and their formation mechanism are currently being intensely studied by the dynamical and modeling groups around the globe after being exposed by this effort and readily made available via the NRL tropical cyclone web page. Saharan Air Layer study has provided needed attention to mapping SAL via Gulfstream G-IV recon for intensity information.

## TRANSITIONS

The tropical cyclone web page has been transitioned to FNMOC since 2001, but new products continue to be added, such as AMSR-E and AMSU-B within the last 12 months. FNMOC now creates and maintains a slightly modified TC web page 24/7! The AMSU intensity effort is mainly 6.4, while relying on 6.3 effort to deal with rain attenuation impact. The “morphing” product has been transitioned to a 6.4 demonstration during the 2005 season with positive feedback from National Hurricane Center and JTWC. The SAL TPW products are used extensively by NOAA-HRD and the Gulfstream dropsonde planning to map SAL extent and interaction with TCs.

## RELATED PROJECTS

This project is closely related to a 6.4 effort sponsored by the Space and Naval Warfare Systems Command (PEO C4I&Space/PMW-180) entitled “Tropical cyclone intensity and structure via multi-sensor combinations”, funded under PE 0603207N. The 6.4 project serves as the transition vehicle, works closely with JTWC, NLMOC and the National Hurricane Center, and currently has taken the software partially developed in this 6.2 task and produced near real-time intensity estimates. Feedback from JTWC, NLMOC, NHC and the TC research community has been extremely positive.

This project works closely with understanding the needs of JTWC/NHC and FNMOC. Feedback is routinely solicited from all operational partners in order to understand how the 6.2 efforts outlined here can best be aligned to answer real world requirements and needs.

## SUMMARY

The use of passive microwave data for TC monitoring has blossomed as a result of this 6.2 effort and the corresponding 6.4 work unit. TC eyewall replacement cycles are currently under intense study as we strive to explain the physical mechanisms responsible for rapid inner-core structural changes. The NRL study using microwave imagery has physically brought these phenomena to the forefront of the TC community. The effort to map Saharan Air Layer (SAL) via passive microwave sensors has proven essential in real-time storm monitoring and is now vital to NOAA G-IV dropsonde operations. Examination of dropsonde moisture data on subsequent storm intensity is required to get the necessary grasp on possible real-time impacts. The automated intensity algorithms using computer vision and AMSU data aloft are gaining acceptance within the research community and are beginning to do the same within the operational centers. A combined algorithm that takes advantage of both Infrared and microwave imagery is being studied in order to create the best possible automated algorithm for use at JTWC and NHC. The vertical integration of the ONR 6.2 effort with the SPAWAR 6.4 work unit has enabled rapid progress and transition of these remote sensing TC monitoring tools.

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